Angular Distribution of Protons from the $Ca^{42}(d,p)Ca^{43}$ Reaction*

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The broad-range magnetic spectrograph was employed in conjunction with a 7-Mev deuteron beam from the MIT-ONR electrostatic generator to obtain angular distributions and relative cross sections for the twelve most intense proton groups corresponding to Ca^{43} levels up to 3.6-Mev excitation. The angular momenta of the captured neutrons were determined by application of deuteron stripping theory.

I. INTRODUCTION

THE energy-level structure of the calcium isotopes is of particular interest with regard to the shell model. Here the unique situation exists that a single shell, the $f_{7/2}$ level, is filled by successive additions of neutrons to a doubly magic core. With this feature in mind, this laboratory has undertaken in the last two years a series of experiments designed to obtain information on the energy-level structure of these nuclei. The work published[1–3] on those calcium isotopes that may be reached by (d,p) reactions or inelastic scattering provides identification and precise measurement of the level energies. The present work is built directly on the work of Braams[3] on Ca^{43}, and was undertaken to provide information on the spins and parities of the Ca^{43} levels as afforded by an interpretation of the angular distribution of the proton groups from the $Ca^{42}(d,p)Ca^{43}$ reaction in terms of deuteron stripping. A brief report of this work has been published.[4] Other papers will discuss similar measurements on the $Ca^{44}(d,p)Ca^{45}$ and $Ca^{40}(d,p)Ca^{41}$ reactions.

II. METHOD

Deuterons were accelerated to 7.01 Mev by the MIT-ONR electrostatic generator. This choice of incident energy was a compromise between the desire to minimize the complications caused by Coulomb effects in the stripping process and the desirability of keeping the energy low enough to insure trouble-free generator operation. The generator and its associated analyzing magnet have been described in an earlier publication.[5] For the present experiment, the analyzing magnet slit system was adjusted to give an energy spread of about 12 kev; the beam current averaged 0.1 microampere.

The proton groups emerging from the target were analyzed in momentum by the broad-range spectrograph, which is described in detail elsewhere.[6] Alignment procedures mentioned in reference 6 insured that the angle between the incident beam and the median plane of the spectrograph was measured with an accuracy better than 10 minutes of arc, and that the solid angle associated with any position in the focal plane was independent of the spectrograph angle.

The solid angle associated with a fixed position on the focal surface varies with position on the photographic plate. As the observation angle is changed, the energy of the proton groups changes slightly. The magnetic field was adjusted accordingly so as to keep the ground-state group at the same position in the focal surface. This adjustment also sufficed to limit the variation in the position on the plates of the other groups arising from calcium to less than 1 cm. As a result, the angular distribution of any single group does not require any correction for variation in solid angle. To obtain a comparison of the intensities of different groups, it was necessary to use the experimentally measured solid angle variation as given in reference 6. This correction was less than 14% for all groups measured in this work. The error in this correction introduces less than a 3% error in the relative intensities.

The spread in the reaction angle of the particles accepted varies with the angular position of the spectrograph. The spectrograph aperture half-angle (measured in the vertical plane) was used at its normal value of $2\frac{1}{2}$ degrees. The corresponding spread in the reaction angle becomes a maximum if the spectrograph is set at zero degrees and vanishes at 90 degrees. At 10 degrees, the lowest spectrograph angle used in this work, the spread in the angle is 0.3 degree. Another contribution to the spread in the reaction angle that depends on the angular position of the spectrograph is the angle under which the horizontal width of the illuminated part of the target is seen from the spectrograph. This contribution becomes a maximum if the spectrograph is set perpendicular to the target plane,

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1 C. M. Braams, Phys. Rev. **101**, 1764 (1956).
2 C. M. Braams, Phys. Rev. **103**, 1310 (1956).
3 C. M. Braams, Phys. Rev. **105**, 1023 (1957).
4 Bockelman, Braams, Buechner, and Guthe, Phys. Rev. **99**, 655(A) (1955).
5 Buechner, Sperduto, Browne, and Bockelman, Phys. Rev. **91**, 1502 (1953).
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which is at about 45 degrees; by collimation of the incoming beam it was made less than 0.2 degree at all angles and at all positions in the focal surface. The spectrograph aperture angle in the horizontal direction is 0.35 degree at the low-energy end of the recorded spectrum and 0.21 degree at the high-energy end. Finally, the directional spread in the incoming beam is limited by collimators to 0.4 degree but actually appears to be less than 0.2 degree. It follows that the largest spread under the conditions of the present experiment was 1 degree.

The targets used were prepared by vacuum evaporation of CaO enriched in Ca^{43} furnished by the Stable Isotopes Division of the Oak Ridge National Laboratory. The isotopic distribution of the calcium in these targets was stated to be: Ca^{40}, 35.4%; Ca^{42}, 64.2%; Ca^{44}, 0.3%; and less than 0.1% of Ca^{43}, Ca^{46}, and Ca^{48}. The targets were from the same set used in the work of reference 3. As noted therein, the difficulties in manufacture were severe, and the targets appear to contain some impurities that are difficult to identify.

The nuclear emulsions were counted in $\frac{1}{2}$-mm strips across the exposed zones. In order to simplify the task of counting the large number of plates necessary to obtain the angular distribution, the emulsions were covered with aluminum foil sufficient to stop deuteron and alpha particles, but thin enough to allow protons to pass through. Thus, all tracks of the proper orientation observed on the plates were counted as protons. At small angles the instrumental scattering is severe, and large numbers of deuterons fell on the foil covering the plates. At angles less than $7\frac{1}{2}$ degrees, protons from the (d,p) reaction in aluminum were sufficient to obscure the plate.

Targets were positioned in the center of an insulated chamber provided with small apertures for the entrance of the beam and the exit of the reaction particles. In order to prevent secondary electrons emitted from the nearby energy-analyzing slits from entering the chamber, the entrance aperture was insulated from the target chamber and biased at −300 volts. The charge collected in the chamber was monitored by an integrator,[7] in

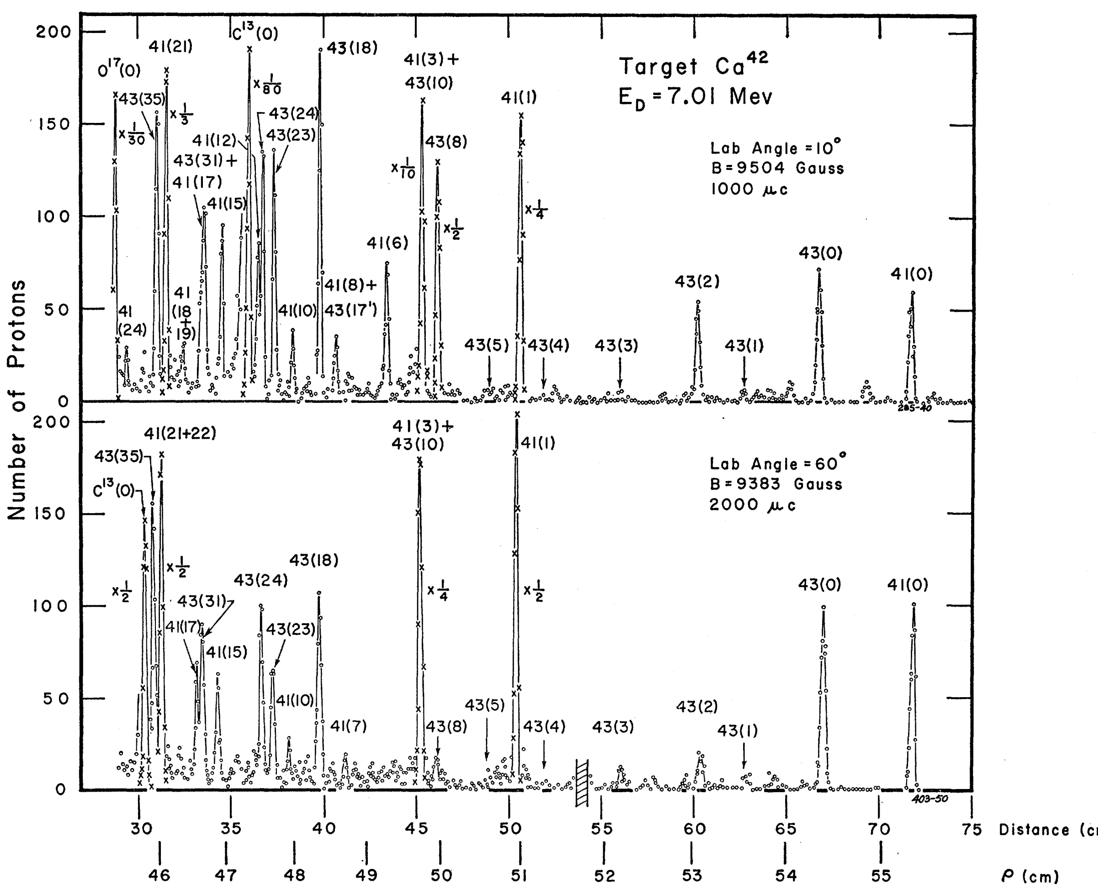

FIG. 1. Graphs of number of protons *versus* position on the photographic plate. Peaks attributed to calcium isotopes are denoted by the mass number of the residual nucleus followed in parentheses by a number assigned in reference 3 denoting the specific level with which the groups are associated.

[7] H. A. Enge, Rev. Sci. Instr. 23, 599 (1952).

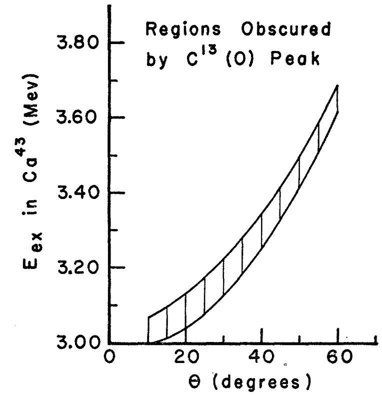

FIG. 2. Excitation region in Ca^{43} obscured by the intense proton group corresponding to the ground state of C^{13} as a function of observation angle.

routine use in the laboratory, which has an accuracy better than 1% over the range of beam currents used. Frequent checks with a megohmmeter insured that the error in current integration from leakage currents was less than 5%.

Because of the marked differences in intensity observed for the different proton groups, it was necessary to obtain at each angle a short exposure of 100 to 200 microcoulombs which produced countable peaks for the intense groups, followed by an exposure of 10 times the length for the weaker groups. The data were obtained in several three-day runs. Three targets were used. Each run was taken without disturbing the target. Every run was started and ended with an exposure at 50 degrees which was used to normalize the runs and insured that no significant amounts of calcium were lost from the target during the long bombardments.

III. RESULTS

Data were obtained in 5-degree intervals from 10 to 60 degrees and in 10-degree intervals from 60 to 100 degrees. The region of the photographic plates corresponding to excitations from 0 to 3.6 Mev in Ca^{43} were counted in $\frac{1}{2}$-mm strips across the exposed zones. Typical momentum analyses are shown in Fig. 1.

The identification of the groups, as well as the excitation energies to which they correspond, was obtained directly from the work of Braams.[3] The numbers used to identify the calcium peaks are those used in references 2 and 3. In addition to the data shown, angular distributions were obtained under identical conditions from a natural calcium target. This work will be reported in detail in a subsequent publication. A comparison of the yields from the calcium reactions on both targets served as a further check on the identifications.

A number of weak groups are clearly evident in Fig. 1 on the 10-degree exposure. The peak at $d=73$ cm has the position expected for a strong deuteron group elastically scattered from the gold-foil backing on the target. Evidently, there was sufficient intensity to produce an appreciable number of protons from a (d,p) reaction in the aluminum foil covering the plate at this position, a conclusion supported by observation in the peak of an unusually large number of tracks incorrectly oriented. The group at $d=69$ cm on the same exposure was observed at several forward angles and is identified as the ground-state group from the $C^{13}(d,p)C^{14}$ reaction. The ground-state group from the $Ca^{42}(d,p)Ca^{43}$ reaction is clearly evident, followed, in the 10-degree exposure, by a series of weaker peaks between 62 and 65 cm distance on the plate. From the previous work,[3] one of these has the position expected for the group corresponding to the first excited state in Ca^{43}. The other peaks in this neighborhood were also present on the Ca^{40} plates with about the same intensity. Since their intensities did not change as the calcium isotopic composition of the target was changed, the latter peaks are presumed to be due to unspecified impurities in the target.

At lower momenta on Fig. 1, the prominent peaks are identified as arising from the calcium isotopes, C^{12}, or O^{16}. The background increases appreciably below $d=50$ cm and may be due for the most part to a superposition of weak peaks. Many are expected from the Ca^{40} reaction,[2] and others may be produced by target contaminants whose spectra have not been studied in detail. It is evident that peaks as weak as that which appears to correspond to the first excited state in Ca^{43} would not be discerned in the data presented. Many of the known levels are not strongly excited in the (d,p) reaction and are not observed here. The calculated positions for groups corresponding to the first, fourth, and fifth excited states[3] in Ca^{43} are indicated by arrows

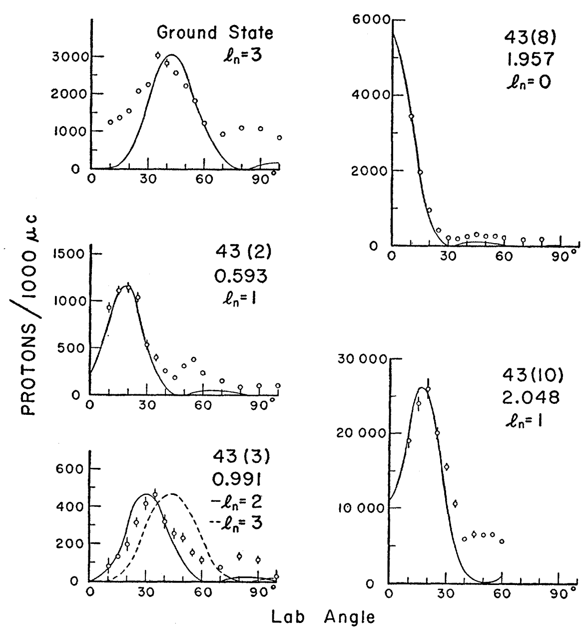

FIG. 3. Angular distributions of proton groups from the $Ca^{42}(d,p)Ca^{43}$ reaction. The stripping curves are calculated using a radius of 6.0×10^{-13} cm.

in Fig. 1. The intense $C^{12}(d,p)$ ground-state group obliterated a region of width corresponding to about 70-kev excitation in Ca^{43}. The location of the area of interference, which might have masked strong groups, is shown as a function of angle in Fig. 2.

Angular distributions were obtained by summing the counts under each peak, subtracting a small background where appropriate, and normalizing to 1000-microcoulomb exposure, using the current integrator. The 50-degree exposure taken at the beginning and end of each run permitted normalization of these results in terms of a particular target, arbitrarily chosen. As may be seen in Fig. 1, in several cases peaks from the $Ca^{42}(d,p)Ca^{43}$ reaction overlapped those from $Ca^{40}(d,p)Ca^{41}$. In these cases, the results of the previously mentioned angular distribution from natural calcium targets (which contain only 0.6% Ca^{42}) were subtracted from the combined peaks to obtain the contribution assignable to Ca^{43} levels. One level, number 17′, in the present experiment, obtained by subtraction from the peak at the position expected for the Ca^{41} 2.967-Mev level has a measurable intensity only in the forward direction and for this reason appears to have been missed in the previous work.[3] However, since it was not possible to obtain an accurate energy shift on this group, it is not possible to state with confidence that it is associated with a level in Ca^{43}. At several angles, the peak marked 41(10) in Fig. 1 was somewhat more intense than that obtained from the natural calcium target, suggesting that it masks a group associated with Ca^{43}. Unfortunately, the two angular distributions involve too few counts to permit a meaningful subtraction.

TABLE I. Relative intensities of proton groups associated with levels in Ca^{43}.

Level	Excitation[a]	Angle of maximum yield	Relative yield at maximum	l_n
0	0	35°	100	1
1	0.373		<7	
2	0.593	20	36	1
3	0.991	35	14	2
4	1.394		<4	
5	1.678		<10	
6	1.904		<7	
7	1.932		<7	
8	1.957	10	100[b]	0
9	1.985		<23	
10	2.048	20	750	1
11	2.069		<270	
12	2.095		<29	
13	(2.107)		<23	
14	2.225		<23	
15	2.250		<23	
16	(2.273)		<14	
17	2.409		<11	
17′	(2.53)	20	13	1
18	2.607	20	84	1
19	2.673		<14	
20	2.696		<14	
21	2.753		<17	
22	2.844		<17	
23	2.880	15	61	1
24	2.947	15	61	1
25	3.027		<11	
26	3.047		<11	
27	3.074		<11	
28	3.094		<7	
29	3.194		<27	
30	3.279		<22	
31	3.293	15	53	...
32	(3.369)		<14	
33	(3.398)		<31	
34	3.419		<31	
35	3.584	15	64	1 or 2

[a] From reference 3.
[b] At 10°.

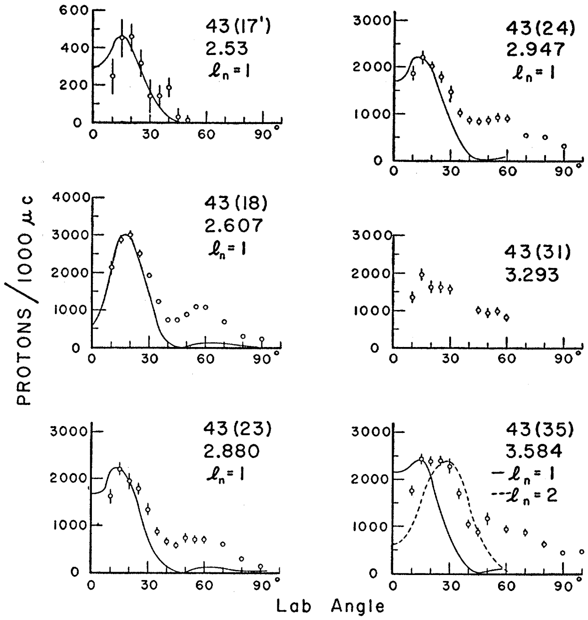

FIG. 4. Angular distributions of proton groups from the $Ca^{42}(d,p)Ca^{43}$ reaction. The stripping curves are calculated using a radius of 6.0×10^{-13} cm.

The results for the eleven prominent groups are plotted in Figs. 3 and 4 and are listed in Table I. Also listed are upper limits on the relative intensity, at any angle studied, for groups corresponding to those levels in Ca^{43} measured in previous work,[3] but not seen in this experiment. The quoted limits do not apply to the masked regions of Fig. 2.

IV. DISCUSSION

It is immediately evident that most of the angular distributions show the strong forward maximum characteristic of the stripping process. In attempting to fit the data with appropriate curves, a choice must be made of the interaction radius. In the present experiment, guidance in this choice is offered by the fact that the values of the orbital momentum of the captured neutron, l_n, appropriate to two of the levels are fixed by the results of previous experiments. The ground-state spin[8] of Ca^{43} and the value of the magnetic moment[8]

[8] C. D. Jeffries, Phys. Rev. 90, 1130 (1953).

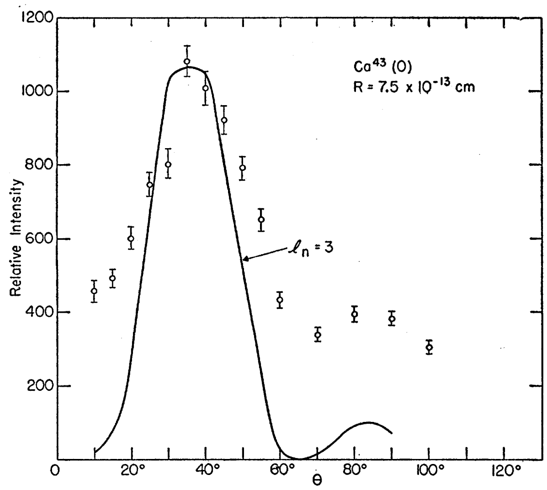

FIG. 5. Angular distribution of proton group associated with formation of the ground state of Ca^{43}, with stripping curve calculated for $R=7.5\times10^{-13}$ cm.

are consistent with the shell-model prediction of a single-particle $f_{7/2}$ state. Since the ground state of Ca^{42} must be 0^+, the angular distribution should be fitted by $l_n=3$. The data for the Ca^{43} ground state from Fig. 3 are reproduced in Fig. 5. The stripping curves in Figs. 5 through 8 were drawn with the aid of the nomograms of Lubitz and Parkinson.[9] Although a recommended value[10] of R, given by $R=(1.22A^{1/3}+1.7)\times10^{-13}$ cm yields a value of 6.0×10^{-13} cm for Ca^{43}, it is seen that a large value of $R=7.5\times10^{-13}$ cm is needed to fit the theoretical maximum of Fig. 5 to the experimental maximum from β-decay evidence.[11] Using the radius 7.5×10^{-13} cm, Fig. 6 shows that the data lie halfway between curves for $l_n=2$ and $l_n=3$. Figures 7 and 8 indicate that the rather small value of $R=5.7\times10^{-13}$ cm, required to fit the $l_n=2$ curve to the second excited state, gives no satisfactory fit to the ground state. It is concluded that the simple theory does not allow the choice of a single radius to fit all the data.

The difficulty in obtaining an appropriate interaction radius may arise from several causes. Examination of the ground-state data shows a relatively large background on which the stripping peak is superposed. If this background is produced by a nonstripping process and if significant interference occurs, the angular distribution predicted by the simple theory may be distorted. Tobocman[12] and Tobocman and Kalos[13] have shown that neglect of the Coulomb forces between the particles involved may lead to serious error. In the present experiment, the proton energies range from 9

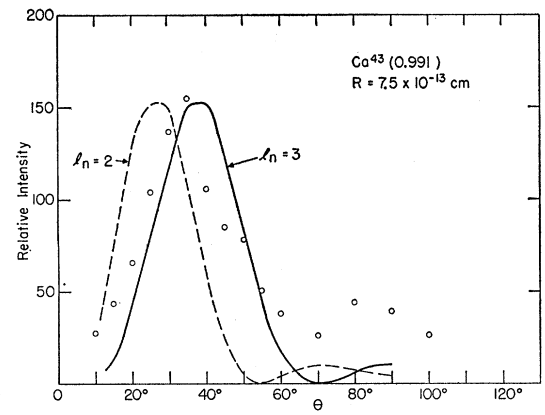

FIG. 6. Angular distribution of proton group corresponding to Ca^{43} level at 0.991 Mev, with stripping curves calculated for $l_n=2$ and 3, $R=7.5\times10^{-13}$ cm.

to 13 Mev, while the deuteron energy is not much greater than the barrier height of 5.6 Mev. However, the computation of such effects is difficult, and no attempt to take them into account was made here. Although it is realized that the simple theory is inadequate to account fully for the present data, it is felt that it may be used to obtain l_n values. Accordingly, the data in Figs. 3 and 4 have been fitted with stripping curves appropriate to a compromise value of $R=6.0\times10^{-13}$ cm. These curves were computed with the aid of the numerical tables prepared by Enge and Graue,[14] which are based on the stripping treatment given by Friedman and Tobocman.[15] An examination of the computations of Tobocman and Kalos[13] shows that the usual effect of a relatively small Coulomb distortion of the incoming and outgoing waves is to move the peak to larger angles and fill in the minima. An l_n assignment corresponding to a theoretical maximum at smaller angles than the data show is therefore preferred to the case where the theoretical maximum is at larger angles than the experimental peak. The preferred l_n assignments are listed in Table I, together with the angle of maximum experimental yield and the relative yield at the maximum corrected for variation in solid angle from group to group.

It may be noted that groups corresponding to the ground states of both Ca^{43} and Ca^{41} are observed with the targets used. Using the relative yield at 35 degrees and the isotopic composition of the enriched calcium as given by Oak Ridge, the ratio of the cross section for formation of the ground state of Ca^{43} to that for formation of the ground state of Ca^{41} is found to be 0.69 ± 0.05. Since the Ca^{43} and Ca^{41} ground-state groups show angular distributions that are identical between the angles of 10 and 60 degrees, a cross-section comparison can also be obtained from the data integrated over this angular range. The ratio obtained in this way is 0.68 ± 0.05.

[9] C. R. Lubitz and W. C. Parkinson, Rev. Sci. Instr. **26**, 400 (1955).

[10] R. Huby, *Progress in Nuclear Physics*, edited by O. R. Frisch (Pergamon Press, London, 1953), Vol. 3.

[11] T. Lindqvist and A. C. G. Mitchell, Phys. Rev. **95**, 444 (1954).

[12] W. Tobocman, Phys. Rev. **94**, 1655 (1954).

[13] W. Tobocman and M. H. Kalos, Phys. Rev. **97**, 132 (1955).

[14] H. A. Enge and A. Graue, Univ. i Bergen, Årbok, Naturvitenskap. Rekke No. 13 (1955).

[15] F. L. Friedman and W. Tobocman, Phys. Rev. **92**, 93 (1953).

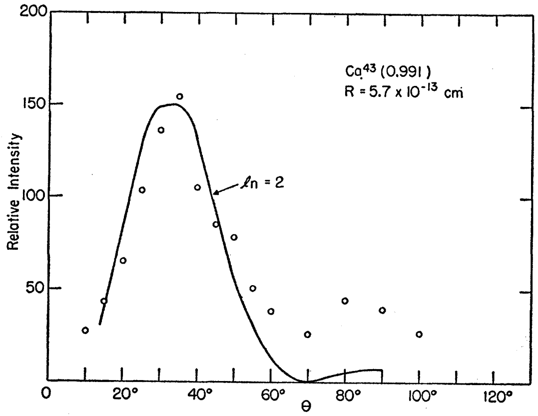

FIG. 7. Angular distribution of proton group corresponding to Ca^{43} level at 0.991 Mev, with stripping curve calculated for $l_n=2$, $R=5.7\times10^{-13}$ cm.

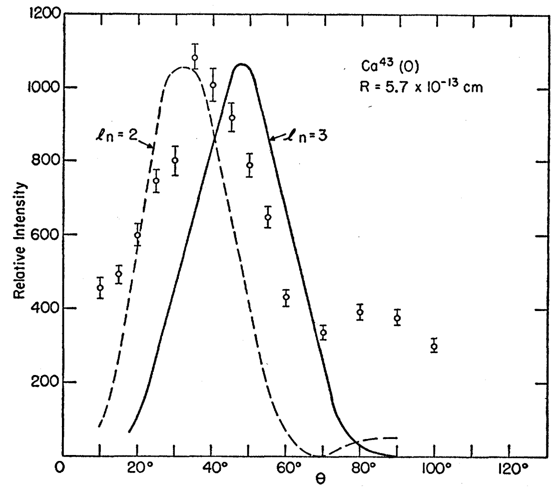

FIG. 8. Angular distribution of proton group associated with formation of the ground state of Ca^{43}, with stripping curves calculated for $l_n=2$ and 3, $R=5.7\times10^{-13}$ cm.

The relation of this work to the β-decay studies[11] has been discussed in detail by Braams.[3] A theoretical interpretation of the angular distributions and relative intensities of the odd-parity levels below 2.1-Mev excitation has been offered by French and Raz.[16] The results of this and other experiments are shown to be consistent with a shell-model picture. Strict j-j coupling predicts

$$\sigma(Ca^{43} \text{ ground state}):\sigma(Ca^{41} \text{ ground state})=0.75,$$

compared to 0.69 observed. That even-parity states exist as low as 1 Mev emphasizes the fact that the Ca^{42} core is rather easily disarranged. One of the five $l_n=1$ levels above 2.6 Mev is probably the "single-particle" $p_{\frac{1}{2}}$ state, that is, $[(f_{7/2})^2]_{J=0}p_{\frac{1}{2}}$, split by 0.5 to 1.5 Mev from the $[(f_{7/2})^2]_{J=0}p_{\frac{3}{2}}$ level at 2.05 Mev. No evidence is found for a $[(f_{7/2})^2]_{J=0}f_{\frac{5}{2}}$ level.

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[16] J. B. French and B. J. Raz, Phys. Rev. **104**, 1411 (1956).

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Angular Distribution of Protons from the $Ca^{44}(d,p)Ca^{45}$ Reaction*†

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The broad-range magnetic spectrograph has been used to study proton groups produced from thin Ca^{44} targets bombarded by 7-Mev deuterons. The angular distributions and relative intensities of groups corresponding to levels in Ca^{45} were measured. Stripping theory was employed to determine the angular momenta of the captured neutrons.

I. INTRODUCTION

THE present work reports one of a series of experiments on the calcium isotopes undertaken at this laboratory over the past three years. The work of Braams[1] is here extended to obtain angular distributions of the proton groups associated with the previously observed levels in Ca^{45} in the range from 0 to 3.5-Mev excitation.

Ca^{45} decays by β^- emission to stable Sc^{45}. The values[2] of spin $\frac{7}{2}$ and magnetic moment 4.75 nuclear magnetons[3]

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† Much of the work reported here is from a joint thesis submitted by the authors to Massachusetts Institute of Technology in partial fulfillment of the requirements for the degree of Master of Science in Physics under the Naval Postgraduate Training Program.
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[1] C. M. Braams, Ph.D. thesis, University of Utrecht, Utrecht, Netherlands, July, 1956 (unpublished).
[2] H. Schuler and T. Schmidt, Naturwissenschaften **22**, 758 (1934); and H. Kopfermann and E. Rasmussen, Z. Physik **92**, 82 (1934).
[3] W. G. Proctor and F. C. Yu, Phys. Rev. **81**, 20 (1951).